# Fuel moisture, forest type, and lightning-caused fire in Yellowstone National Park

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The occurrence and behavior of lightning-caused fires in Yellowstone National Park were summarized for 17 years (1972–1988) during a prescribed natural fire program. Both ignition (occurrence) and spread (stand replacing fire activity) of fires were strongly influenced by fuel moisture and forest cover type. Fuel moisture estimates of 13% for large (>7.6 cm) dead and downed fuels indicated a threshold below which proportionately more fire starts and increased stand replacing fire activity were observed. During periods of suitable fuel moisture conditions, fire occurrence and activity were significantly greater than expected in old-growth, mixed-canopy lodgepole pine (*Pinus contorta* Dougl. var. *latifolia*) and Engelmann spruce – subalpine fir (*Picea engelmannii* Parry – *Abies lasiocarpa* (Hook.) Nutt.) forest types, and significantly less than expected in the successional lodgepole pine forest types. During periods of extended low fuel moisture conditions (drought), sustained high winds significantly reduced the influence of forest cover type on stand replacing fire activity. These extreme weather conditions were observed during the later stages of the 1988 fire season, and to a lesser extent, for a short duration during the 1981 fire season. The Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forest type typically supported little stand replacing fire activity, even though a preponderance of fire starts was observed.

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Des données sur la fréquence et le comportement des feux de foudre dans le parc national de Yellowstone, portant sur une période de 17 ans (1972–1988) d'application d'une politique de gestion des incendies naturels, ont été assemblées. L'ignition (fréquence) et la propagation (activité des feux causant le remplacement des peuplements) étaient toutes deux fortement influencées par l'humidité des combustibles et le type de couvert forestier. Une teneur en humidité des combustibles de 13%, pour des gros combustibles (>7,6 cm) morts et à plat, constitue un seuil en-deça duquel un plus grand nombre d'incendies démarrent et une augmentation de l'activité des feux sont observée. Au cours des périodes où les conditions d'humidité des combustibles étaient favorables, la fréquence et l'activité des incendies étaient significativement plus importantes que prévu dans les vieilles forêts mélangées des types forestiers de pins de Murray (*Pinus contorta* Dougl. var. *latifolia*) et d'épinettes d'Engelmann – sapins subalpins (*Picea engelmannii* Parry – *Abies lasiocarpa* (Hook.) Nutt.) et significativement moins importantes que prévu dans les types forestiers pionniers de pins de Murray. Pendant les périodes prolongées de basse teneur en humidité des combustibles (sécheresse), la présence de vents forts et continus a réduit significativement l'influence des types de couvert forestier sur l'activité des feux de remplacement des peuplements. Ces conditions météorologiques extrêmes ont été observées à la fin de la saison des feux de 1988 et, dans une moindre mesure, lors d'une courte période pendant la saison des feux de 1981. Les peuplements de sapin de Douglas (*Pseudotsuga menziesii* (Mirb.) Franco) n'ont typiquement supporté qu'une faible activité des feux de remplacement des peuplements, même si une prépondérance à l'ignition a été observée.

[Traduit par la rédaction]



## Introduction

Considerable fire research has focused on fire history documentation (e.g., Romme and Despain 1989; Romme 1982; Romme and Knight 1981; Arno 1980; Taylor 1969, 1974), fire ecology (see reviews by Kozlowski and Ahlgren 1974; Wright and Bailey 1982), or prevention and control measures under various conditions (Barney 1979). Scant information, however, exists in regard to the occurrence, duration, behavior, and influence of fuel and fuel moisture on naturally occurring fire initiation and propagation at the landscape level (e.g., Pickford *et al.* 1980).

Natural fire behavior interactions have been observed in Yellowstone National Park (YNP) since the establishment of a prescribed natural fire policy in 1972 (Despain and Sellers 1977). Park administrators, recognizing fire as an integral forest process, allowed lightning-caused fires to burn without human interference unless park developments or lands outside the park's boundaries were threatened. There were 262 prescribed natural fires monitored from 1972 to 1988 under this program. Monitoring such fires included gathering detailed weather and fuels information in conjunction with daily fire spread.

Between 1972 and 1988, YNP experienced a broad spectrum of local weather and fire conditions. Summers of high precipitation with minimal fire activity (e.g., 1982–1984), dry conditions with substantial burning (e.g., 1979 and 1981, a combined 13 000 total hectares burned), and a year of extreme burning (1988, >321 000 ha burned) were observed. Fire behavior results from the interaction between weather and fuels, and recent studies' have emphasized the understanding of natural fire behavior and constraints on fire initiation and spread (Taylor and Fonda 1990; Turner and Romme 1991; Rothermel 1988).

In this paper, we summarize prescribed natural fire activity in YNP from 1972 to 1988 and identify the influences of fuel moisture and forest cover type on fire initiation and spread.

## Study area

YNP lies mostly in the northwest corner of Wyoming, United States, primarily between 44 and 45°N latitude and 110 and 111°W longitude and covers about 850 000 ha. It consists of large volcanic plateaus of Quaternary rhyolitic rocks surrounded by mountains of predominantly andesitic rocks of Eocene age. Summers are usually dry, receiving about 32 mm of rain per month. The mean annual

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temperature near the center of the park is about 1 or 2°C (Despain 1990). The fire season usually lasts from mid-June to middle or late September.

The park is about 83% forested. Areas where lodgepole pine (*Pinus contorta* Dougl. var. *latifolia*) is the dominant seral species and Engelmann spruce (*Picea engelmannii* Parry) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) are climax species cover about 77% of the forested area. Stands dominated by whitebark pine (*Pinus albicaulis* Engelm.) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) account for most of the remainder of the forested area.

The forest cover type classification of YNP breaks the continuous process of forest succession into five recognizable stages based on stand structure (Despain 1977, 1990).

Successional cycles are initiated when fire or other large-scale disturbance kills the forest overstory. The period of re-establishment of lodgepole pine over the next 40–50 years, to the beginning of canopy closure, is considered the LP0 stage. If the previous disturbance was fire, fuels in this stage consist of abundant large, sound or rotten, standing or fallen fire-killed trees, a well-developed herb–grass layer usually too green to burn, and a few small dead woody fuels. Once canopy closure occurs, dense stands of small-diameter, or "doghair," lodgepole pine commonly persist for the period 50–150 years postburn. This is the LP1 stage. Forest floor fuels consist of a few rotten logs and a relatively sparse herb–grass layer underlain by a thin carpet of fallen needles. The predominant fuel, however, is the dense and compact crowns typical of even-aged stands. As these stands begin to break up, a shade-tolerant understory of Engelmann spruce – subalpine fir begins to develop on sites with fertile soils. On poor soils lodgepole pine forms the understory. This is described as the LP2 stage and exists during the period 150–300 years postburn. In the early years of this phase ground fuels remain relatively sparse, but flammability increases with stand development as the overstory thins and the understory proliferates. Finally, LP3 stands >300 years postburn are characterized by a mixed canopy of pine, spruce, and fir, with an equally diverse understory. A high dead and downed woody fuel component coupled with a varied vertical arrangement of live understory fuels is present. Understory species eventually replace the mixed overstory and, with ample groundwater and no disturbance, reach the Engelmann spruce – subalpine fir (spruce–fir) stage. This is the "climax" stage, which persists until the next major disturbance.

A different kind of terminal stage develops on midelevation rhyolitic or other extremely dry soils. Here, lodgepole pine dominates the understory, resulting in a multiaged lodgepole pine canopy. These old-growth lodgepole pine forests have a high dead and downed fuel component, but lack the Engelmann spruce – subalpine fir understory of LP2 and LP3 forests.

Whitebark pine can exist as a minor over- and under-story component in the stages previously described, but is usually the dominant canopy species at high elevations >2560 m. Fuel components are similar to the early LP2 stage in monotypic whitebark pine forests, but more like the LP3 stage when whitebark pine is mixed with spruce and fir.

Douglas-fir forests are mostly limited to the northern one-third of the park at elevations between 1829 and 2316 m (6000–7600 ft) along the Yellowstone and Lamar River valleys. Dead and downed woody fuel components are usually less than in the lodgepole pine forests. Douglas-fir forests in YNP are usually associated with a well-developed herbaceous layer and interspersed with sagebrush (*Artemisia tridentata* Nutt.) meadows and aspen (*Populus tremuloides* Michx.).

The successional sequence as presented above is similar to the stand initiation, thinning, transition, and steady-state phases proposed by Oliver (1981) and Christensen (1988). More detailed descriptions and photographs are available elsewhere (Despain 1990; Romme and Despain 1989).

## Methods

All fire and weather information was obtained from records archived in the Yellowstone Fire Management Office.

### *Fuel moisture*

An estimate of the percent moisture content of dead and downed roundwood fuels >7.6 cm in diameter is designated as Thousand-Hour Timelag Fuel Moisture (THRFM) (Deeming *et al.* 1978). This calculated value is a part of the National Fire Danger-Rating System used by land management agencies throughout the United States. THRFM is used as a measure of long-term moisture conditions or as a drought severity indicator. For this study THRFM values used were calculated from daily fire weather observations at the Mount Sheridan fire weather station located in the south central portion of the park at an elevation of 3142 m. Absolute THRFM values may differ at lower elevations or when compared with field measurements, but seasonal patterns at this station probably reflect seasonal moisture patterns for the subalpine regions of the park as a whole. THRFM was used here to compile (*i*) a distribution of values for 1766 days archived for the 1965–1988 fire seasons, (*ii*) an average daily THRFM value from archived data (1965–1988) for the time period 1 July to 30 September, when the greatest fire activity occurs, and (*iii*) the distribution of 347 of the 407 lightning-caused fires (1972–1988) per THRFM value. The remaining 60 fires occurred before the station was in operation for the season.

### *Forest type and fire mapping*

The distribution and area of different forest types throughout the park were compiled from 1 : 15 840 color aerial photographs taken from 1969 to 1971 (Despain 1990). Forest type information for 265 of 273 lightning-caused fire ignitions from 1979 to 1988, regardless of management action, was obtained by plotting Universal Transverse Mercator coordinates for each initial fire location on 1 : 62 500 forest type maps. Accurate site-specific coordinates were not available for the remaining 8 fires. Similarly, all fire ignitions prior to 1979 were located using township, range, and section, making future reference to site-specific coordinates virtually impossible.

Assuming that each square land unit in YNP was available to receive lightning and that loci were not related to forest type, our null hypothesis was that lightning-caused fire occurrence in each forest type was proportional to the occurrence of each forest type within the total forested area of the park. Following $\chi^2$ analysis, a 90% "confidence family" (Neu *et al.* 1974) was calculated for the observed proportion of fire ignitions by forest type and compared with expected proportions in determining statistical significance.

The area of fire-killed forest overstory was mapped for 11 prescribed natural fires >324 ha (800 acres) for the years 1972–1987 from 1 : 16 000 color infrared aerial photographs taken in 1987. The data were transferred to 1 : 62 500 forest type maps to obtain the area of each forest type burned. The resulting totals are referred to in this paper as 1972–1987 totals and were mapped at a 4-ha minimum resolution.

Because of the magnitude and complexity of the 1988 fire season, remote sensing techniques utilizing Landsat satellite imagery (e.g., Johannsen and Sanders 1982) were employed to map burned areas at a 2-ha minimum resolution. Four burn classes (i.e., canopy, mixed, nonforested, undifferentiated) were identified (Despain *et al.* 1989), and generated burn maps were overlaid with YNP forest type maps using a geographic information system (GRASS software) to produce a matrix of burn classes by forest type. The mixed burn (combination of unaffected and blackened trees) and canopy burn (overstory consumed) classes were combined to represent the area affected by stand-replacing fire. The term stand-replacing fire is used hereafter to define fire that killed all or nearly all of the overstory by way of crown fire or high-intensity surface fire.

The portions of all major fire complexes within park boundaries, including three human-caused fires that originated outside and burned into the park, were incorporated into final area totals under the assumption that human-caused fires behaved no differently from lightning-caused fires and suppression efforts had little effect. Burn pattern across the landscape was of primary interest, and the data are referred to in this paper as 1988SEASON.

A third approach to assess associations between fire behavior and the YNP forest types was also employed. Fire activity up to and including 21 July 1988 was compiled as noted above and compared

TABLE 1. Fire seasons summary, Yellowstone National Park, 1972–1988

| | Total no. of fires | No. of lightning-caused fires | Prescribed natural fires No. | Prescribed natural fires Area (ha) | Total area burned (ha) | % normal precipitation[a] |
|---|---|---|---|---|---|---|
| 1972 | 21 | 15 | 4 | 1 | 2 | 155 |
| 1973 | 33 | 24 | 2 | 1 | 59 | 103 |
| 1974 | 38 | 28 | 7 | 336 | 529 | 60 |
| 1975 | 26 | 18 | 9 | 1 | 2 | 75 |
| 1976 | 30 | 19 | 15 | 628 | 649 | 166 |
| 1977 | 29 | 18 | 8 | 4 | 27 | 119 |
| 1978 | 24 | 12 | 6 | 2 | 6 | 65 |
| 1979 | 54 | 29 | 14+4[b] | 4257 | 4546 | 73 |
| 1980 | 25 | 21 | 16 | 1 | 2 | 122 |
| 1981 | 64 | 57 | 26+2[b] | 8191 | 8335 | 77 |
| 1982 | 20 | 13 | 9 | 1 | 1 | 118 |
| 1983 | 7 | 4 | 4 | 1 | 1 | 137 |
| 1984 | 11 | 11 | 9 | 1 | 1 | 138 |
| 1985 | 53 | 43 | 42 | 13 | 13 | 90 |
| 1986 | 33 | 27 | 27 | 1 | 1 | 114 |
| 1987 | 35 | 29 | 29 | 388 | 390 | 117 |
| 1988 | 45 | 39 | 15+14[b] | —[c] | 321 273 | 32 |
| Total | 548 | 407 | 262 | 13 823[d] | 335 833 | |
| Avg. | 32 | 24 | 15 | 864[d] | 910[d] | |

[a]Based on the 30-year period 1950–1980, June through September only.
[b]Second number denotes later, limited suppression efforts along the flanks of large fires initially allowed to burn unhindered.
[c]Data not yet available to differentiate areas burned, while fire complexes were managed, as prescribed natural versus suppression entities.
[d]Excludes 1988 data.

with 1972–1987 data to reflect trends most likely to occur during more typical fire seasons. This early- to mid-season data, herein referred to as 1988JULY, was similarly compared with 1988SEASON data to differentiate early- and late-season fire activity. The 1988JULY data reflect fire activity when (*i*) fires were of a size previously encountered under the prescribed natural fire policy, (*ii*) the smaller fires had not yet burned together to form larger fire complexes, and (*iii*) human-caused fires did not yet occur. Here, our null hypothesis was that early weather patterns, and therefore fire behavior patterns until 21 July 1988, were no different from what was previously experienced from 1972 to 1987.

The predisposition of stand-replacing fire for a given forest type was calculated using Cole's coefficient of interspecific association (CIA) (Cole 1949). Here, the area of stand-replacing fire in a particular forest type was compared with the availability of that unburned forest type as well as the combined burned and unburned area of all other forest types in a $2 \times 2$ contingency table. A linear coefficient of interspecific association, ranging from $-1$ to 1, was generated, which reflects a negative, zero, or positive predisposition for crown fire. A negative association suggests that stand-replacing fire and the particular forest type are not likely to co-occur; the degree of departure identifies the magnitude of likelihood. Statistical significance was also determined by calculating a standard error of the coefficient to generate a $t$-statistic (Cole 1949).

The overall null hypothesis was that stand-replacing fire was random and occurred within each forest type in proportion to the frequency of each forest type in the park. If, for example, 30% of the total park forested area exists as LP3, then 30% of the crown fire activity should occur in LP3 if there is no association. Distribution of forest cover types in YNP is not random, but is influenced by bedrock and precipitation (Despain 1990). Fire activity, however, has been widely dispersed, and 42% of the 730 000 forested park hectares have been affected to some degree by fire over the past 15 years. The assumptions and methodology therefore appear sufficiently robust to allow for generalizations of fire behavior.

## Results

### *Fire history, 1972–1988*

From 1972 through 1988, a total of 548 fires were recorded (Table 1). Five additional fires originated outside and burned into the park during 1988. Of the 407 lightning-caused fires, 242 were initially allowed to burn without human interference. Modified suppression (i.e., suppression along a portion of the fire flank or of spot fires across predetermined landmarks, etc.) was employed on an additional 14 lightning-caused fires in 1988, 2 in 1981, and 4 in 1979, so that 262 total fires were managed equivalently to prescribed natural fires. During the initial 5 years of the program (1972–1976), 36% ($n$ = 37) of the lightning-caused fires were allowed to burn, whereas later in the program during the wetter 1983–1987 period, 97% ($n$ = 111) were managed as prescribed natural fires. The cause for the difference is that more caution was exercised during the early years of the program and later, fire managers recognized that fire had little potential to exhibit extreme fire behavior during wetter periods.

Overall, 83% ($n$ = 218) of all prescribed natural fires self-extinguished before reaching 0.5 ha in size. Of the remaining fires, 8 burned within each of the size classes 0.5–4.0, 5.0–40, and 41–404 ha; 9 ranged between 405 and 4047 ha; and 11 smaller fires burned together to form two different complexes >4048 ha.

The most active fire seasons (1979, 1981, 1988) had rainfall considerably below normal (Table 1). Some dry summers (1975, 1978) were apparently associated with infrequent lightning occurrences, while other wet summers (1976, 1987) had short-duration rain-free periods sufficient for limited fire activity.

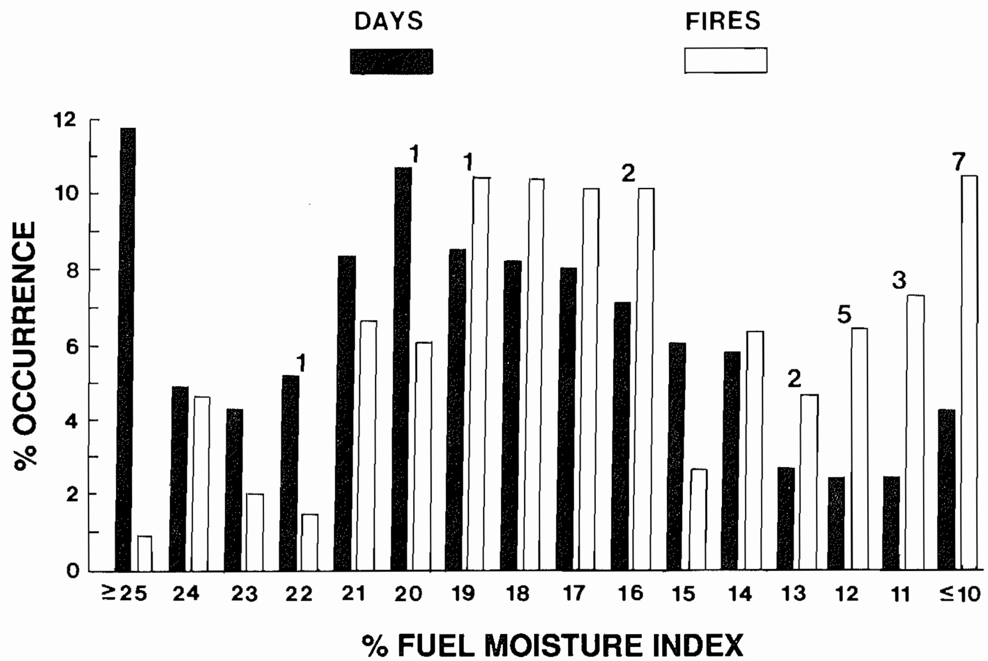


FIG. 1. Distribution of Mount Sheridan THRFM values ($n$ = 1766 days, 1965–1988) and the distribution of lightning-caused fires ($n$ = 347 of 407, 1972–1988) per THRFM value. The number of fires eventually exceeding 325 ha ($n$ = 22), by THRFM value on the initial starting date, is shown above the bars.



*THRFM, fire occurrence, and fire activity*

THRFM values for 1766 days during the 1965–1988 fire seasons ranged from 8 to 32% (Fig. 1). The relative frequency of THRFM values approximates a normal distribution, slightly skewed to the "wet" end, whose mean, mode, and median are 18.6, 20, and 19.5%, respectively.

The occurrence of 347 of 407 lightning-caused fires (1972–1988) per THRFM value, on the other hand, demonstrates a nonsymmetrical, bimodal distribution that is negatively skewed to the "dry" end of the fuel moisture range. Mean and median values occur at 16.3 and 17.5%, respectively, with a broad major mode centered between 17 and 18% and another minor mode at ≤10%. Although the majority of lightning-caused fires take place during the more frequently occurring moisture levels, there is a proportional increase in lightning-caused ignitions during the rare occurrence of dry conditions.

The average daily THRFM values plotted across seasons also suggest that typical fire conditions are relatively stable and wet (Fig. 2). When compared with selected years, seasons with many fire ignitions and large areas burned are characterized by rapidly drying moisture conditions in early July with accompanying low values in middle to late summer. Seasons with little fire activity approximate or deviate above the average daily trend and result from frequent precipitation. Most seasons, however, fluctuate between wet and dry conditions, allowing limited opportunity for fire activity. Fire severity at any date throughout the season can therefore be attributed to the degree of departure from average moisture conditions.

It appears that an increase in fire ignitions and crown fire activity occurs at THRFM values approaching 13% (Figs. 3 and 4). This value may be an important threshold in moisture level because fires quickly result in readily observable smoke columns and, if fuel conditions are optimal, exhibit extreme fire behavior (see Fig. 1). Any subsequent increase in moisture, typical of the usual midsummer arrival of moist maritime tropical air into the region, will decrease fire ignitions and rate of fire perimeter growth. Once large fires became established, however, they were not completely extinguished until the arrival of late-autumn snows.

*Forest type, fire occurrence, and fire activity*

Lightning-caused fires were not distributed randomly throughout the park, but occurred proportionately more frequently in selected old-growth forests ($\chi^2$ = 87.1, $p$ < 0.001). For 265 of 273 lightning-caused fires from 1979 to 1988, mature stands of spruce–fir, Douglas-fir, and LP3 experienced significantly more ignitions ($p$ < 0.10) than expected based on forest type occurrence (Table 2). These stands collectively occupied 34.3% (250 390 ha) of the total park forested area, yet experienced 58.5% ($n$ = 155) of the lightning-caused fires. Successional lodgepole pine (LP1, LP2) and old-growth multiaged lodgepole stands, on the other hand, experienced significantly fewer ignitions ($p$ < 0.10) than expected. Lightning-caused fire occurrence in LP0 and whitebark pine forests was proportional to forest type availability. All of the large fires observed since the inception of the prescribed natural fire program (Fig. 1) originated in late LP2, LP3, and spruce–fir forest types.

Once fires became established, the total area burned by stand-replacing fire in the different forest types was not in proportion to the distribution of those forest types ($\chi^2$ = 7995, $p$ < 0.001). Of the 9041 ha of stand-replacing fires from 1972 to 1987, old-growth spruce–fir and LP3 had a significant positive association with fire (CIA ± SE = 0.08 ± 0.003, $t$ = 32.8 and 0.45 ± 0.006, $t$ = 74.2, respectively, $p$ < 0.001; Fig. 5). These forest types occupied 28.5% (208 050 ha) of the total YNP forested area, yet 70.5% (6374 ha) of the area burned was in these forest types. Young-growth successional

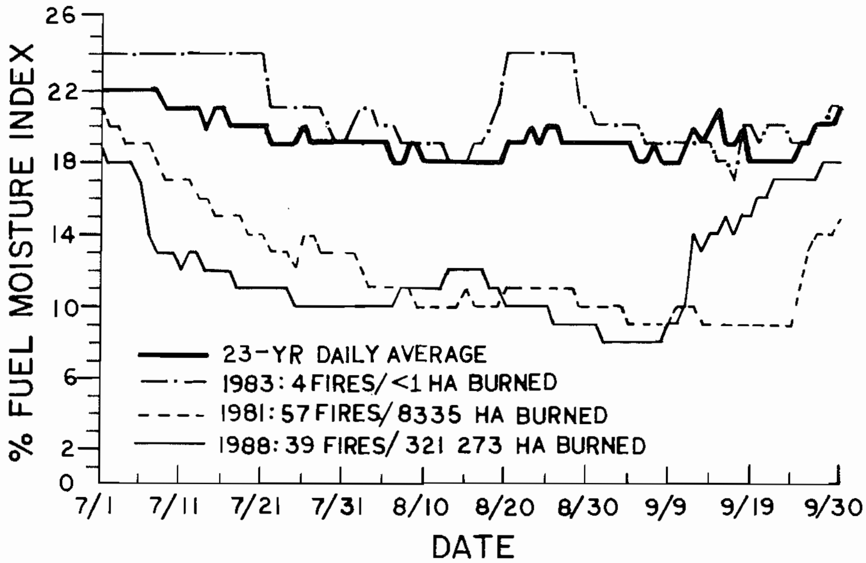


FIG. 2. Seasonal THRFM trends of the Mount Sheridan fire weather station for years of varying fire intensity (1981, 1983, 1988) compared with average daily values over 23 years (1965–1988). The number of lightning-caused fires, and the total area burned during each respective fire season, are given. Dates are presented as month/day.

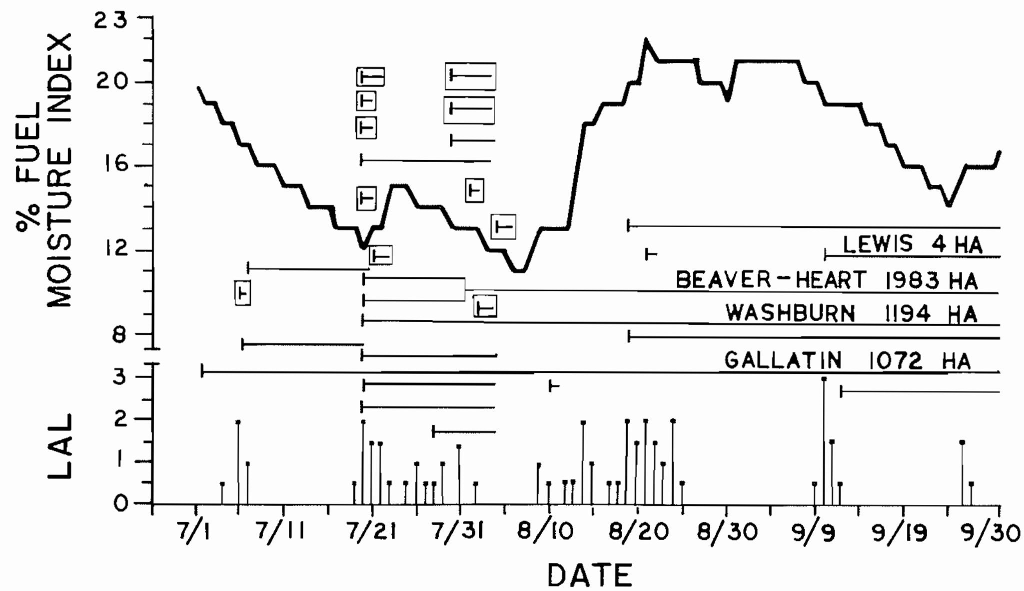


FIG. 3. Lightning activity level (LAL), and the occurrence and duration of lightning-caused fires, in relation to THRFM trends for the 1979 fire season. Data were taken from the Mount Sheridan fire weather station. LAL (Deeming *et al.* 1978) is a subjective, numerical rating from 1 (no lightning) to 6 (the infrequent lightning bust of greater than four cloud to ground discharges per minute). The average of two daily readings, adjusted for 0 to reflect no lightning, was used here as a measure of the timing and intensity of an ignition source. Fires that were suppressed are boxed. The final size of all fires exceeding 1 ha is shown. Dates are presented as month/day.

lodgepole pine stages (LP0, LP1, LP2), multiaged lodgepole pine forests, and whitebark pine forests showed a moderate to strong significant negative association with stand-replacing fire (CIA ranged from –0.64 to –0.31, $t$ ranged from 5.56 to 45.6, $p < 0.001$). The Douglas-fir forest type did not experience stand-replacing fire during this time period (CIA = –1.0).

Similar trends in fire activity were observed for 4010 ha burned through 21 July 1988 (Fig. 5). Stand-replacing fire was not proportional to the distribution of forest types ($\chi^2 = 1999$, $p < 0.001$). The LP3 forest type again showed a strong significant positive association with crown fire (CIA = 0.35 ± 0.008, $t = 43.8$, $p < 0.001$). Most other forest types, including Douglas-fir again demonstrated a moderate to strong significant negative association (CIA ranged from –0.95 to –0.17, $t$ ranged from 6.6 to 18.9, $p < 0.001$; except in the case of multiaged lodgepole pine forests, where CIA = –0.14 ± 0.056, $t = 2.5$, $p < 0.05$). The spruce–fir forest type, on the other hand, showed a slight nonsignificant positive association with crown fire (CIA = 0.0005, $t = 0.15$, $p > 0.50$) and burned in proportion to forest type availability.

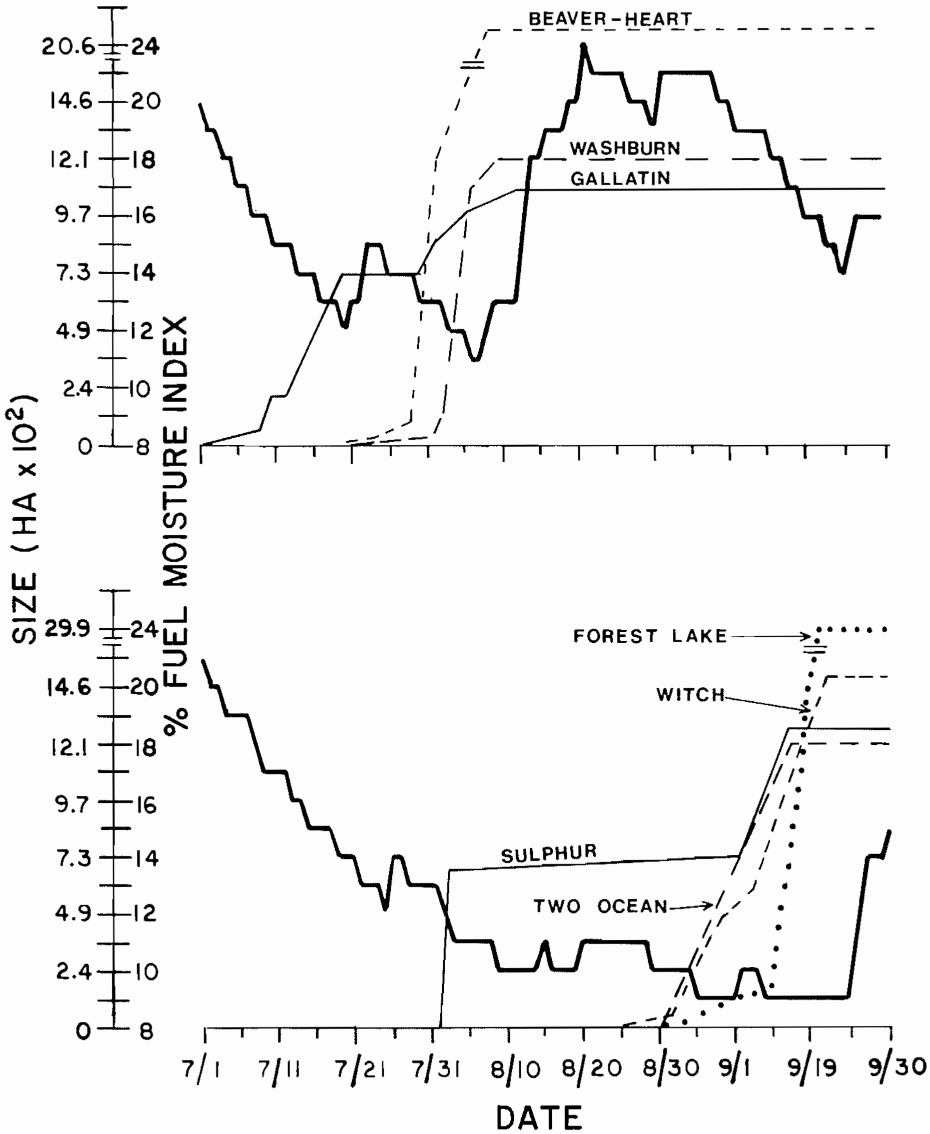


FIG. 4. Major fire growth in relation to Mount Sheridan THRFM trends for the 1979 (top) and 1981 (bottom) fire seasons. Fire growth was temporarily interrupted on the 1981 Sulphur fire as the flaming front encountered an older 1956 burn of 628 ha. Subsequent growth resulted from later activity along the fire flanks. Dates are presented as month/day.

CIA values by forest type did not differ significantly between the 1976–1987 and 1988JULY data sets (Wilcoxin paired-sample test, $T = 9$, $p > 0.10$).

The final burn pattern of 1988 was somewhat different from the previous trends, even though stand-replacing fire activity remained nonproportional to forest type availability ($\chi^2 = 33\,037$, $p < 0.001$; Fig. 5). For the 252 911 ha of stand-replacing fire in 1988, LP3 again demonstrated a significant positive but weaker association with fire (CIA = 0.14 ± 0.0009, $t = 151.1$, $p < 0.001$). The LP1 forest type, representing forests 50–150 years old, reversed in trend and demonstrated a slight positive yet significant association (CIA = 0.002 ± 0.0005, $t = 3.86$, $p < 0.001$). The spruce–fir forest type similarly reversed in trend and showed a slight significant negative association with crown fire (CIA = –0.04 ± 0.007, $t = 6.14$, $p < 0.001$). All other forest types continued to demonstrate a significant negative association (CIA ranged from –0.39 to –0.04, $t$ ranged from 7.0 to 68.0, $p < 0.001$). CIA values differed significantly for forest types when comparing 1988SEASON with 1988JULY (Wilcoxin paired-sample test, $T = 4.5$, $p < 0.10$) and with 1972–1987 ($T = 7$, $p < 0.10$). CIA for all forest types in 1988SEASON receded toward zero when compared with 1988JULY and 1972–1987, suggesting that forest type had a decreased, yet still measurable, influence on fire behavior during the later stages of the fire season (see Fig. 5).

## Discussion

### *Forest types*

The likelihood of lightning-caused fire ignitions and stand-replacing fire behavior is greatest in the LP3 forest type of YNP. Significantly more ignitions and a moderate to strong association with crown fire were observed. The spruce–fir forest type demonstrated similar trends, but they were less marked. Pioneer (LP0), successional (LP1, LP2), and multi-aged lodgepole pine forests had significantly fewer ignitions

TABLE 2. The percentage of lightning-caused fires and area burned, by forest type, in Yellowstone National Park, 1972–1988

| Forest type[a] | Total park forested area, pre-1972 % | Total park forested area, pre-1972 ha×10³ | % lightning-caused fires ($n$ = 265) | Area burned (ha×10³)[b] 1972–1987 | Area burned (ha×10³)[b] 1988JULY | Area burned (ha×10³)[b] 1988SEASON |
|---|---|---|---|---|---|---|
| LP0 | 2.0 | 14.7 | 1.9 | 0.11[c] | 0.06[c] | 6.19 |
| LP1 | 9.3 | 67.5 | 2.6* | 0.58 | 0.02 | 23.65 |
| LP2 | 34.9 | 254.9 | 21.1* | 1.15 | 1.16 | 76.02 |
| LP3 | 22.9 | 167.2 | 34.0* | 5.17 | 1.99 | 82.87 |
| LP | 7.4 | 54.1 | 4.2* | 0.32 | 0.25 | 17.89 |
| S–F | 5.6 | 40.5 | 13.6* | 1.20 | 0.22 | 13.03 |
| DF | 5.8 | 42.2 | 10.9* | 0 | 0.12 | 8.90 |
| WB | 12.1 | 88.5 | 11.7 | 0.52 | 0.19 | 24.37 |
| Total | | 729.6 | | 9.05 | 4.01 | 252.92 |

NOTE: *, Statistically significant deviation from expected result ($p < 0.10$) based on forest type occurrence.

[a]LP0–LP3, pioneer, early, middle, and late lodgepole pine, respectively; LP, multiaged climax lodgepole pine; S–F, Engelmann spruce – subalpine fir; DF, Douglas-fir; WB, whitebark pine.

[b]1972–1987, the total area burned by stand-replacing fire during that time period; 1988JULY, area burned from June through 21 July 1988; 1988SEASON, final burn totals for 1988.

[c]Includes areas initially burned from 1972 to 1987 that reburned in 1988.

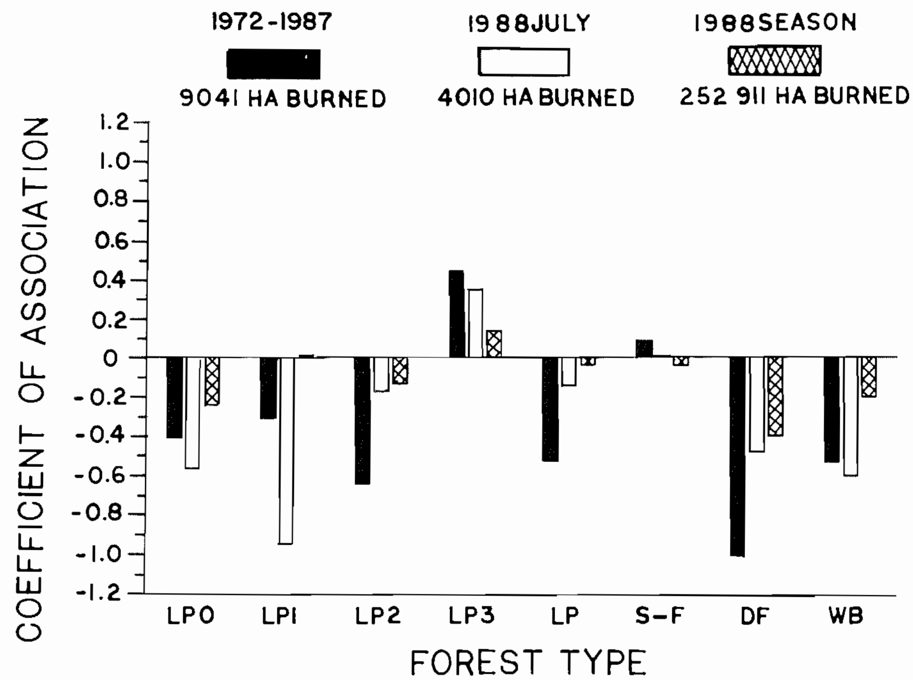


FIG. 5. Coefficient of association values, by forest type, demonstrating a positive or negative susceptibility for stand-replacing fire. Values range from −1 to 1, with zero suggesting no association. All values are significant at $p < 0.001$, except multiaged lodgepole pine 1988JULY, where $p < 0.05$, and spruce–fir 1988JULY, which is nonsignificant. 1972–1987, the total area burned by stand-replacing fire during that time period; 1988JULY, area burned from June through 21 July 1988; 1988SEASON, final burn totals for 1988. LP0–LP3, pioneer, early, middle, and late lodgepole pine; LP, multiaged climax lodgepole pine; S–F, Engelmann spruce – subalpine fir; DF, Douglas-fir; WB, whitebark pine.

and a negative association with crown fire. The LP1 forest type, because of the density of pole-sized trees and continuous crown fuels, would sometimes burn under extremely low fuel moisture conditions coupled with high winds.

By demonstrating a negative exponential age-class distribution, Despain (1983) concluded that multiaged lodgepole pine forests are not prone to stand-replacing fire. The analysis reported here further supports this conclusion. Because of the limited water holding capacity and low nutrients of rhyolite-derived soils upon which multiaged lodgepole pine stands are found, the understory lacks Engelmann spruce – subalpine fir regeneration. Given that all of the old-growth lodgepole pine forest types have a relatively high dead and down woody fuel loading, it appears that crown fire activity within these YNP forest types is more dependent on understory Engelmann spruce – subalpine fir regeneration than on dead fuel loading.

The other old-growth forest types of the YNP landscape demonstrate a different susceptibility to fire. Although the whitebark pine forest type experienced lightning-caused ignitions in proportion to forest type distribution, the high elevation – high moisture environment apparently does not favor crown fire during most years. The Douglas-fir forest type uniquely demonstrated a high frequency for lightning-caused ignitions, yet crown fire activity was observed only in the extreme fire season of 1988.

Houston (1973) reported and partially associated a fire return interval of 20–25 years to native-American burning for this same portion of the park. The data for his study were taken from fire-scarred Douglas-fir on the edge of the stands or lone trees. Houston's (1973) emphasis was on fire return interval in adjacent grasslands and shrublands and should not be confused with fire occurrence and spread in Douglas-fir forest type as reported here.

It may be that the fuel arrangement of Douglas-fir forests is not favorable for crown fire development from within, but will accept crown fire from adjacent highly flammable forest types (as occurred in 1988) depending on the velocity and duration of wind. On the other hand, suppression efforts in Douglas-fir forests may have prevented those fire starts with burning potential from being realized; only those fires with little potential were allowed to burn. It has been our observation that the majority of lightning-caused fires in the lower elevation Douglas-fir forests occur early in the fire season before live surface fuels have cured. More opportunity to observe fire behavior in Douglas-fir forests is needed for a complete assessment of that forest type's fire regime and of the influence of native-American burning in the YNP landscape. Data presented here demonstrate that Douglas-fir forests in YNP have a different relationship with fire than higher elevation lodgepole pine forests.

*The interaction of fuel moisture and forest type*

Lightning-caused fires occur in YNP throughout the fuel moisture continuum, but in a given fire season either relatively large areas burn or little fire activity is observed. Some initial threshold level of fuel moisture must therefore be attained to promote fire spread provided lightning ignitions occur in favorable fuels (Turner and Romme 1991).

In the high-elevation lodgepole pine forests of YNP, this threshold level is apparently achieved when fuel moisture estimates for large (>7.6 cm) dead and down woody fuels reach 13%. At or below 13%, lightning ignitions quickly result in observable smoke columns and, if fuel conditions are optimal, quickly exhibit fire spread. Taylor and Fonda (1990) implied a similar phenomenon by demonstrating that smaller (<7.6 cm) dead woody fuels attained maximum flammability when fuel moisture estimates ranged between 20 and 22% in subalpine fir forests of Olympic National Park.

At threshold moisture conditions in YNP stand-replacing fire activity is constrained by forest type. The flammable LP3 and spruce–fir forest types burn readily, while the Douglas-fir, whitebark pine, successional lodgepole pine (LP0, LP1, LP2), and multiaged lodgepole pine forest types do not. Strong winds, however, are able to buffer or perhaps supersede this fuel moisture – forest type influence for short durations. The highly flammable LP3 forest type, for instance, will exhibit localized torching and subsequent perimeter growth during low wind – optimal fuel moisture conditions. Crown fire activity in LP1, on the other hand, is maintained only during high wind periods when fuel moisture is considerably below the threshold value. Following the cessation of wind, LP1 lacks the fuel structure to generate and promote continued crown fire activity.

Long periods with fuel moisture levels below 13% were observed in both 1981 and 1988, yet the quantitative change in forest type susceptibility for stand-replacing fire was not observed in 1981. The majority of fire activity in 1981 occurred during September, whereas extreme fire behavior occurred throughout the 1988 season. Stand-replacing fire activity in 1988 became more widespread across forest types and probably resulted from the combination of (*i*) prolonged drought conditions that influenced both live and dead fuels, (*ii*) continued high winds associated with the passage of at least 6 different cold fronts in August and early September, and (*iii*) the large expanse of active fire perimeter contributing to fire spread.

Future research efforts should consider the juxtaposition of forest types across the YNP landscape in predicting the outcome of prescribed natural fires under various hypothetical moisture and wind conditions. Such efforts would have important resource management implications and would further illustrate the value of natural areas such as YNP where ecological processes and landscape structure can be observed.

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